Recent results for tau LFV decays from Belle

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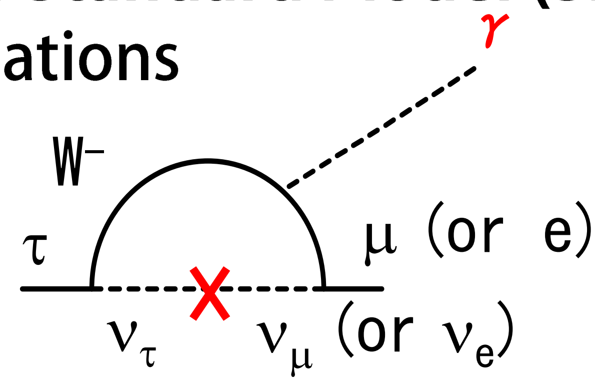
Introduction

Lepton flavor violation (LFV) in charged leptons

⇒ **negligibly small probability in the Standard Model (SM)**
even taking into account neutrino oscillations

$$Br(\tau \to \ell\gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$$

(EPJC8 513 (1999))



Observation of LFV is a clear signature of New Physics (NP)

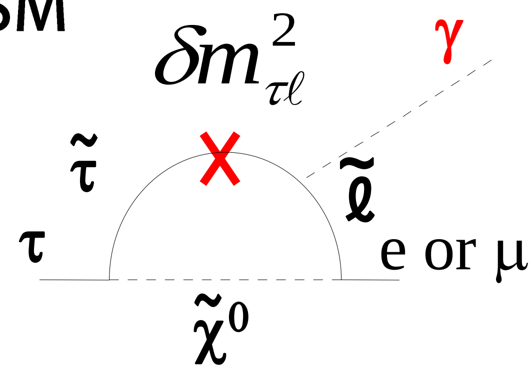
•Many extensions of the SM predict LFV decays.
→These branching fractions could be enhanced as high as current experimental sensitivity.

Tau lepton :
- The heaviest charged lepton
- Many possible LFV decay modes

⇒Ideal place to search for LFV

LFV in SUSY

SUSY is the most popular candidate for BSM among new physics models

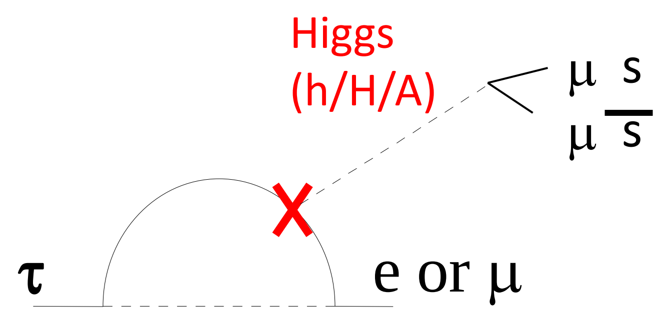


> naturally induce LFV at one-loop due to slepton mixing

$\tau \to \ell\gamma$ mode has the largest branching fraction in SUSY-Seesaw (or SUSY-GUT) models

When sleptons are much heavier than weak scale

> LFV associated with a neutral Higgs boson (h/H/A)



Higgs coupling is proportional to mass

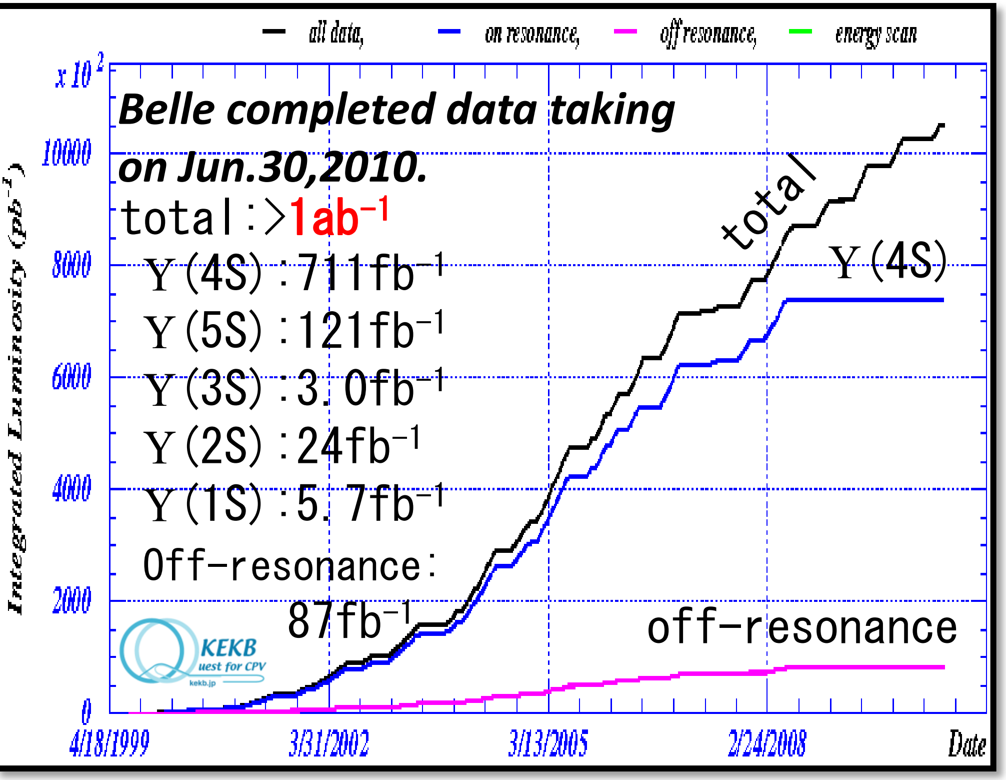
$\Rightarrow \mu\mu$ or $s\bar{s}$ (η, η' and so on) are favored and Br is enhanced more than that of $\tau \to \mu\gamma$.

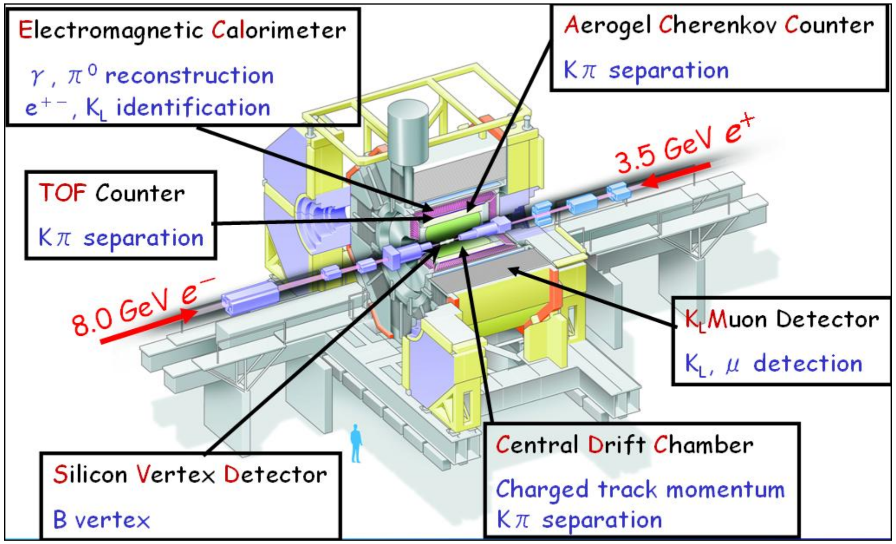
To distinguish which model is favored, various searches for τ LFV are important!

update $\tau \to \ell M^0$ ($M^0 = \pi^0, \eta, \eta', \rho^0, K^{*0}, \overline{K}^{*0}, \omega, \phi$), $\ell\ell\ell$

KEKB/Belle

B-factory: E at CM = Υ(4S)
e^+(3.5 GeV) e^-(8 GeV)





Good track reconstruction and particle identification

	mID	eID
Efficiency	~85%	~90%
Fake rate	~3%	~0.1%

~9x10^8 ττ at Belle

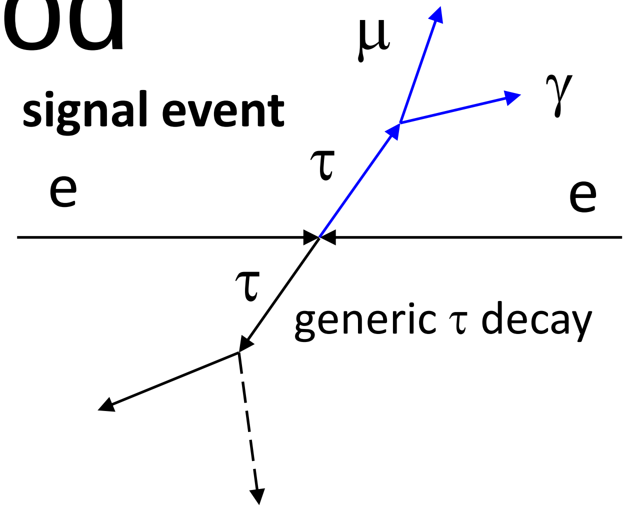
σ(ττ)~0.9nb, σ($b\bar{b}$)~1.1nb

A B-factory is also a τ-factory!

World-largest data sample!

Analysis method

- $e^+e^- \rightarrow \tau^+\tau^-$
  - → 1 prong + missing (tag side)
  - → $\mu+\gamma$ (signal side)

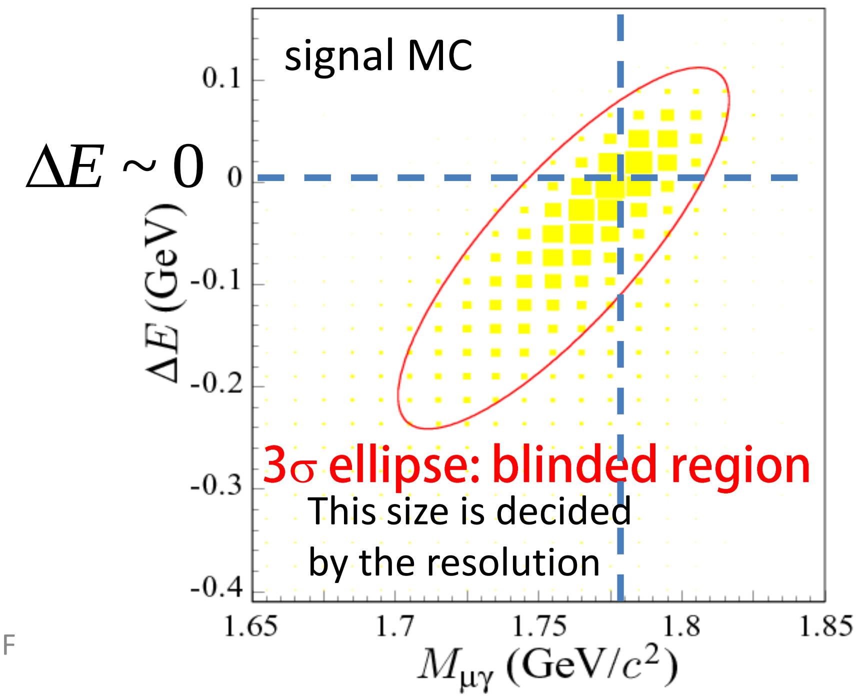


Signal extraction: $M_{\mu\gamma}$-ΔE plane

$$M_{\mu\gamma} = \sqrt{(E_{\mu\gamma}^2 - p_{\mu\gamma}^2)}$$

$$\Delta E = E_{\mu\gamma}^{CM} - E_{beam}^{CM}$$

$M_{\mu\gamma} \sim m_\tau$

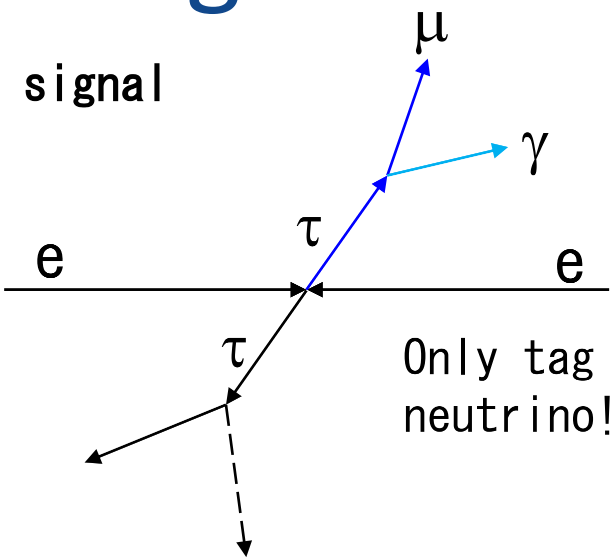


Blind analysis
⇒Blind signal region

Estimate number of BG in the singal region using sideband data and MC
→UL is evaluated by F&C method (POLE).

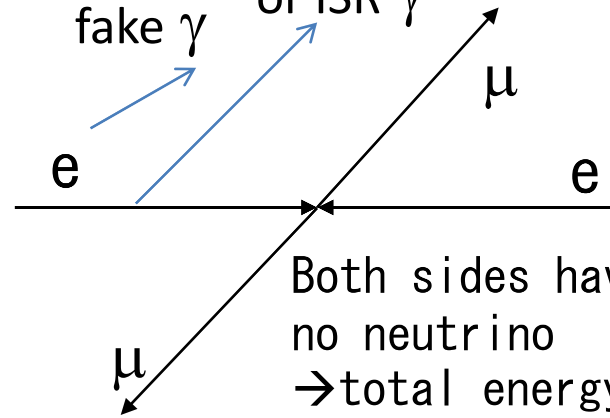
Signature of signal and background

signal



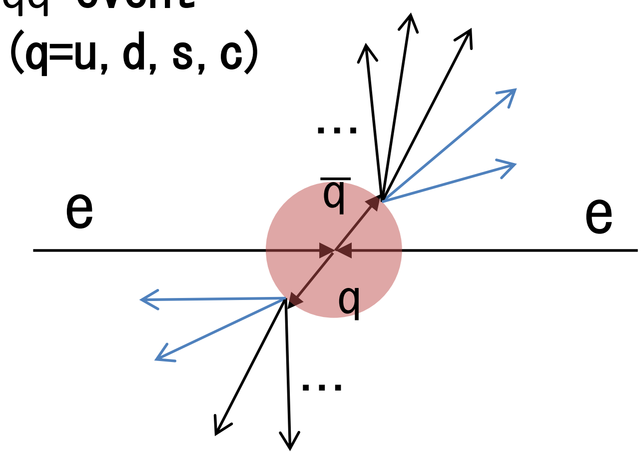
Only tag side has neutrino!

μμ event



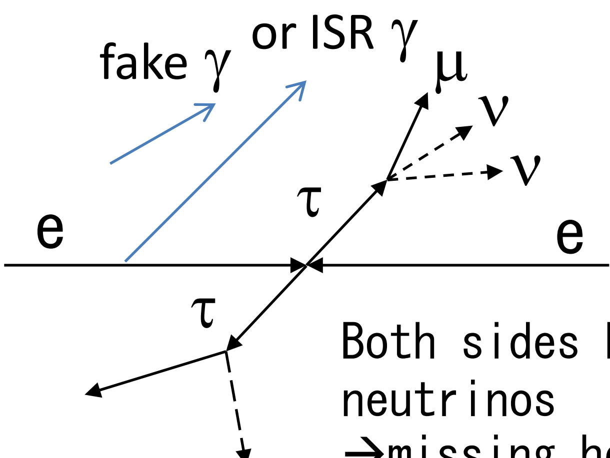
Both sides have no neutrino
→total energy is equal to beam energy.

$q\bar{q}$ event
(q=u, d, s, c)



Both sides have many tracks and photons.
→No. of photons decreases this kind of BG's.

SM ττ event



Both sides have neutrinos
→missing helps us to reject this kind of BG's.

Feature of Analysis for $\tau\to\mu\gamma$, $\mu\eta$, $\mu\mu\mu$

Generally,

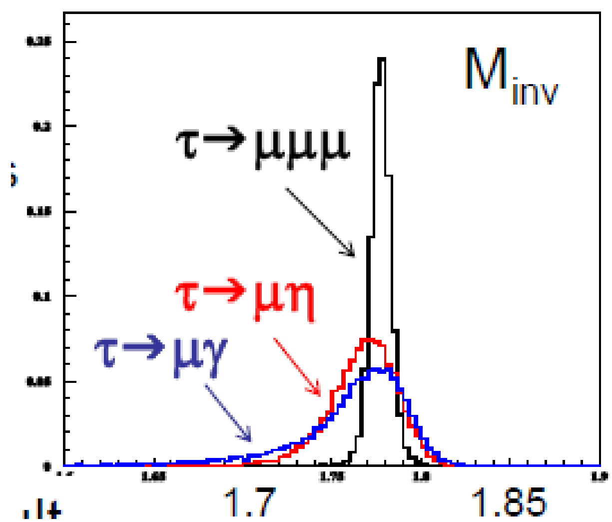
- γ in signal decay : difficult to distinguish from ISR or fake γ, makes resolution worse than in all-charged modes.
- lepton: good efficiency and low fake rate, good resolution.

	BG rejection	Mass resolution
$\tau\to\mu\gamma$	very hard	bad (γ)
$\tau\to\mu\eta$	hard (but η mass window helps)	bad (2γ, but η mass window helps)
$\tau\to\mu\mu\mu$	easy(μID x3)	good (only charged tracks)

Here, we discuss only $\eta\to\gamma\gamma$ subdecay mode.

Besides, since $\tau\to\mu\gamma$ has only 2 particles, less kinematical information than that for other decays

	Main BG
$\tau\to\mu\gamma$	$ee\to\mu\mu+\gamma$, $\tau\to\mu\nu\nu+\gamma$, $\tau\to\pi\nu+\gamma$
$\tau\to\mu\eta$	$ee\to\mu\mu+\gamma\gamma$, $\tau\to\mu\nu\nu+\gamma\gamma$, $\tau\to\pi\nu+\gamma\gamma$
$\tau\to\mu\mu\mu$	$ee\to\mu\mu\mu\mu$, $ee\mu\mu$



Search for $\tau \rightarrow \ell\ell\ell$

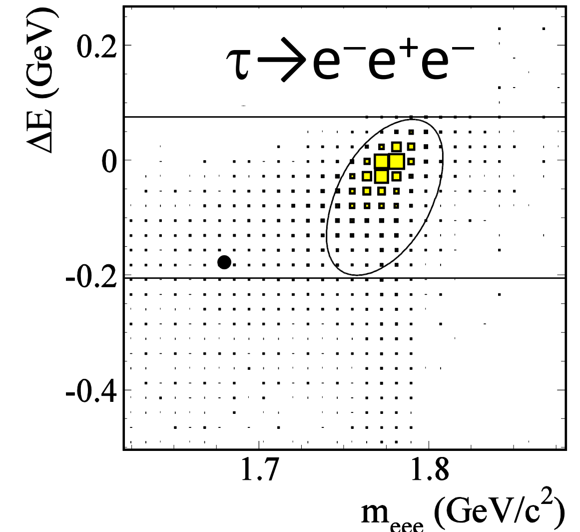
Update analysis from 543fb^{-1} → 782fb^{-1}

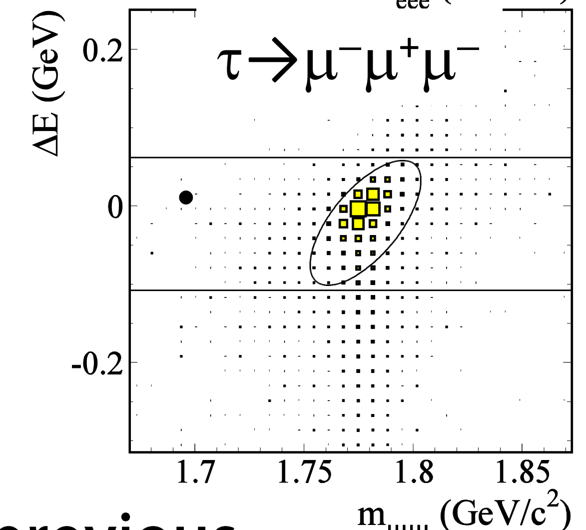
➡ Apply almost same event selection as previous analysis

We observe no events in signal region for all modes

PLB 687, 139 (2010)

Mode	Eff. (%)	N_{BG}^{EXP}	UL ($\times 10^{-8}$)
$e^-e^+e^-$	6.0	0.21±0.15	**2.7**
$\mu^-\mu^+\mu^-$	7.6	0.13±0.06	**2.1**
$e^-\mu^+\mu^-$	6.1	0.10±0.04	**2.7**
$\mu^-e^+e^-$	9.3	0.04±0.04	**1.8**
$\mu^-e^+\mu^-$	10.1	0.02±0.02	**1.7**
$e^-\mu^+e^-$	11.5	0.01±0.01	**1.5**





→(1.3-1.6) times more stringent results than previous.

Search for $\tau \to \ell P^0 (= \pi^0, \eta, \eta')$

previous result

Data : 401 fb^{-1} @ Belle, 339 fb^{-1}@BaBar

(PLB648,341(2007)) (PRL98,061803(2007))

•To obtain high detection efficiency,

$\eta(\eta')$ is reconstructed from $\gamma\gamma(\rho^0\gamma)$ as well as $\pi\pi\pi^0(\pi\pi\eta)$.

$\mathcal{B}<(0.8\text{-}2.4)\times 10^{-7}$ at 90%CL

•**New search with 901fb^{-1} data sample**

- To obtain better resolution, $\eta(\eta')$-momentum is evaluated by $\eta(\eta')$-mass-constrained fit.
- Differently from the previous analysis, selection criteria are set mode by mode.

ex.) previous → new

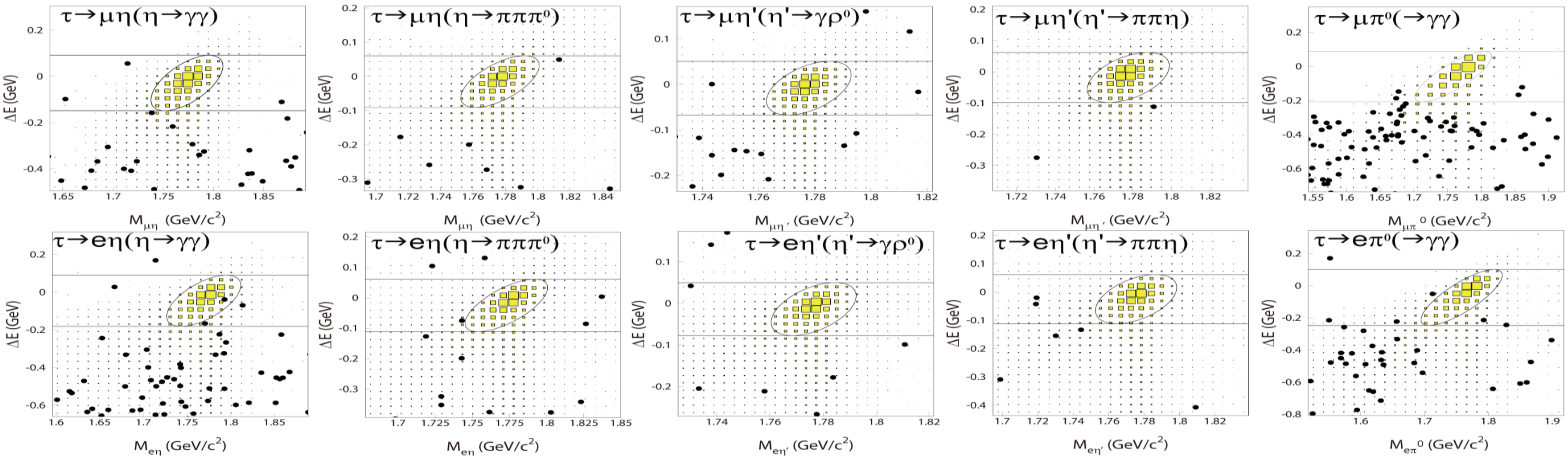
commonly required $P_\ell^{CM}<4.5$GeV/c → $P_\mu^{CM}/\sqrt{s}<0.38$ for $\tau\to\mu\eta$
not required for $\tau\to e\eta$
$0.15<P_\mu^{CM}/\sqrt{s}<0.38$ for $\tau\to\mu\pi^0$
$P_e^{CM}/\sqrt{s}<0.38$ for $\tau\to e\pi^0$

- For $\tau\to\mu\eta$, Neural network (NN) selection is also introduced.

Finally, the efficiency is higher than previous (around 1.5x in average), while similar background is achieved. (#BG < 1)

Result for $\tau \to \ell P^0 (=\pi^0, \eta, \eta')$

Belle preliminary



$\tau \to$	Eff.	N_{BG}^{exp}	UL ($\times 10^{-8}$)	$\tau \to$	Eff.	N_{BG}^{exp}	UL ($\times 10^{-8}$)
$\mu\eta(\to\gamma\gamma)$	8.2%	0.63±0.37	3.6	$\mu\eta'(\to\pi\pi\eta)$	8.1%	0.00+0.16-0.00	10.0
$\mu\eta(\to\pi\pi\pi^0)$	6.9%	0.23±0.23	8.6	$\mu\eta'(\to\rho^0\gamma)$	6.2%	0.59±0.41	6.6
$\mu\eta$(comb.)			**2.3**	$\mu\eta'$ (comb.)			**3.8**
$e\eta(\to\gamma\gamma)$	7.0%	0.66±0.38	8.2	$e\eta'(\to\pi\pi\eta)$	7.3%	0.63±0.45	9.4
$e\eta(\to\pi\pi\pi^0)$	6.3%	0.69±0.40	8.1	$e\eta'(\to\rho^0\gamma)$	7.5%	0.29±0.29	6.8
$e\eta$(comb.)			**4.4**	$e\eta'$ (comb.)			**3.6**
$\mu\pi^0(\to\gamma\gamma)$	4.2%	0.64±0.32	**2.7**	$e\pi^0(\to\gamma\gamma)$	4.7%	0.89±0.40	**2.2**

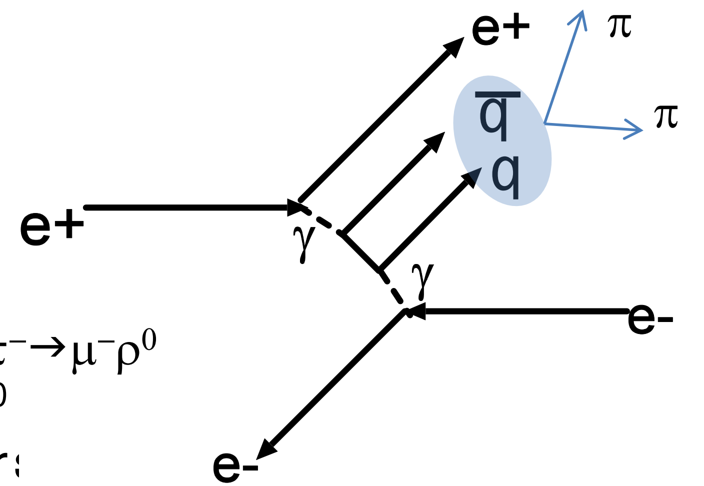
→(2.1-4.4) times more stringent results than previous (401fb^{-1})

Search for $\ell V^0(=\rho^0, K^{*0}, \overline{K^{*0}}, \omega, \phi)$

previous result
Data : 543 fb^{-1} @ Belle, 451 fb^{-1}@BaBar
(PLB664,35(2008)) (PRL100,071802(2008),PRL103,021801(2009))

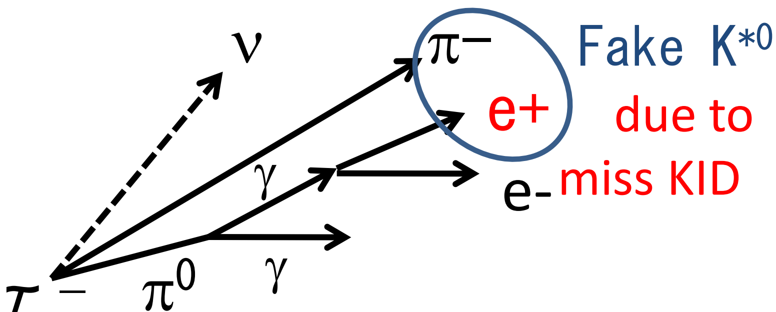
- Differently from ℓP^0, 2photon process could be large backgrounds for ℓ=e.

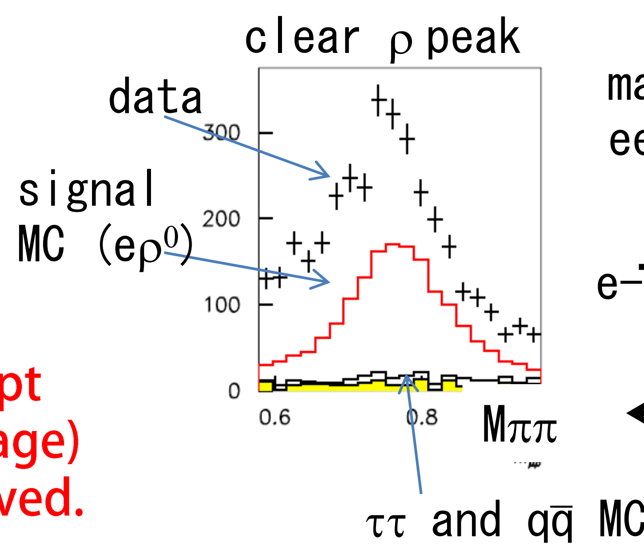
$\mathcal{B}$<(0.3-1.9)x10^{-7} at 90%CL

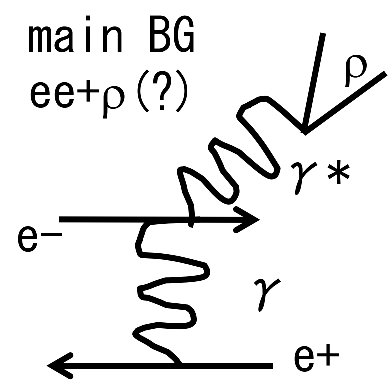


- **New search with 854fb^{-1} data sample**

- Detailed background study:
It turns out that not only 2photon process but also ee+X process become large background for $\tau^-\to\mu^-\rho^0$ and $\tau^-\to\pi^-\pi^0\nu$ with γ-conversion becomes e$^-$K^{*0}/K^{*0} backgrounds because e/h(=π, K) separation is wors in low momentum region.

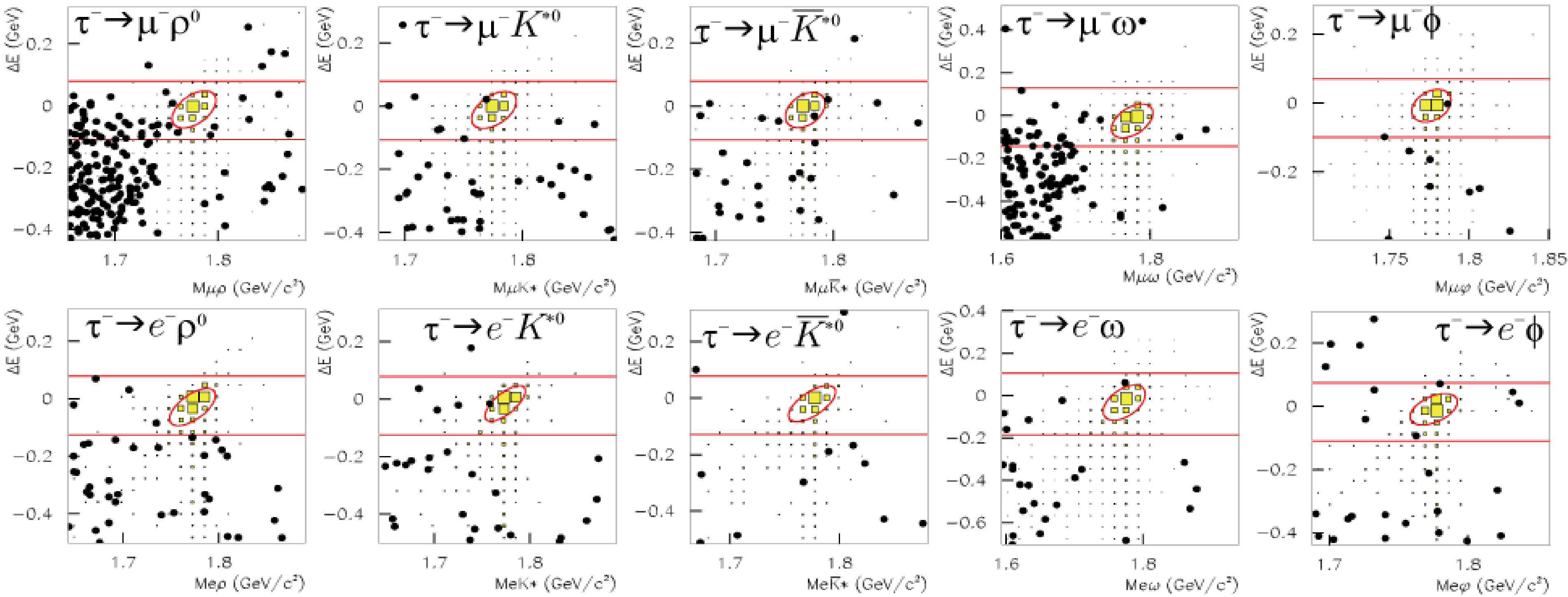






Finally, higher or similar efficiency is kept
(around 1.2x in average)
while similar background level is achieved.

Result for $\ell V^0(=\rho^0, K^{*0}, \overline{K^{*0}}, \omega, \phi)$

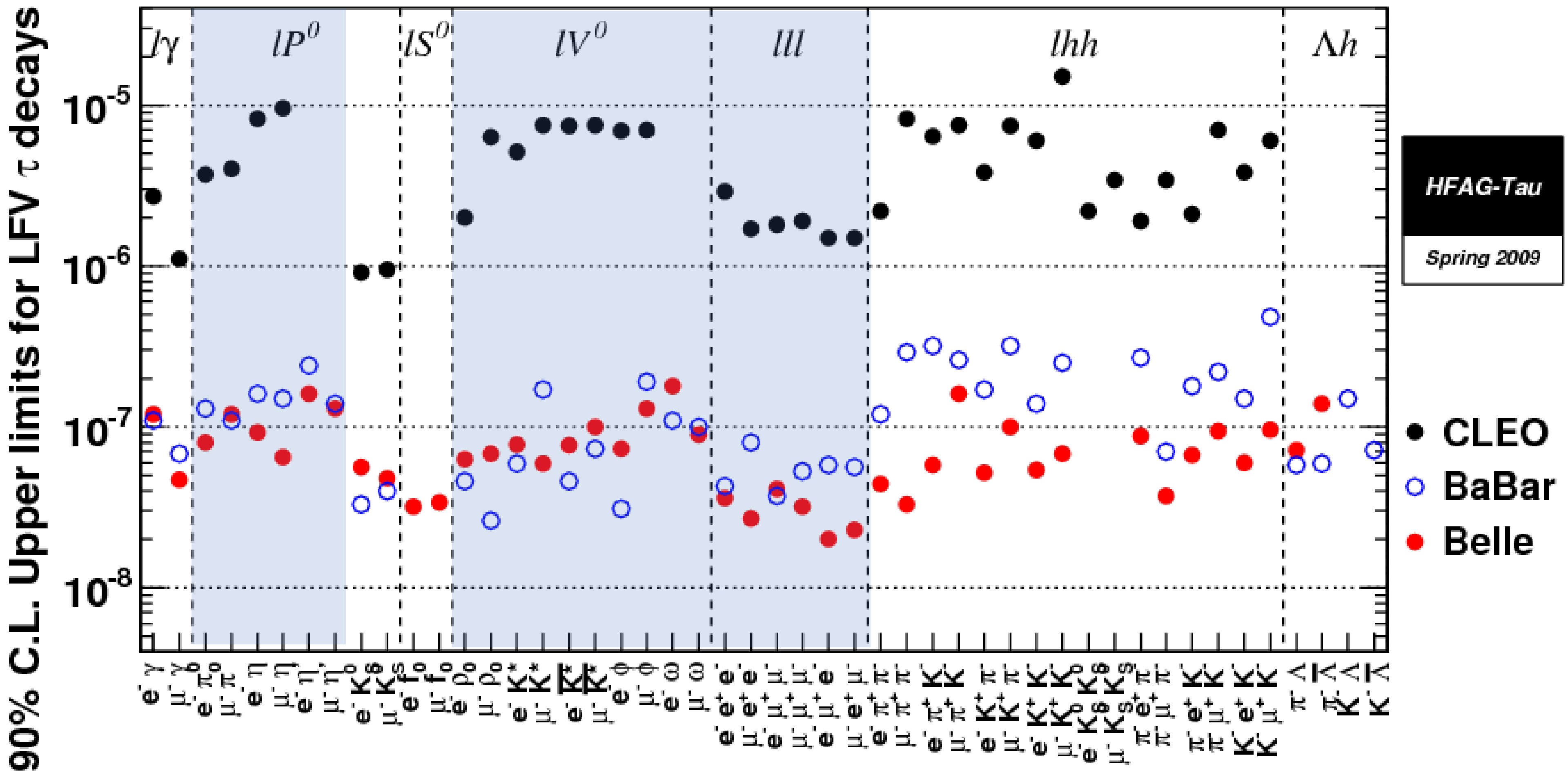


$\tau^- \to$	Eff.	N_{BG}^{exp}	UL $(\times 10^{-8})$	$\tau^- \to$	Eff.	N_{BG}^{exp}	UL $(\times 10^{-8})$
$e\text{-}\rho^0$	7.6%	0.29 ± 0.15	**1.8**	$e\text{-}K^{*0}$	4.4%	0.39 ± 0.14	**3.2**
$\mu^-\rho^0$	7.1%	1.48 ± 0.35	**1.2**	$\mu^- K^{*0}$	3.4%	0.53 ± 0.20	**7.2**
$e\text{-}\phi$	4.2%	0.47 ± 0.19	**3.1**	$e\text{-}\overline{K^{*0}}$	4.4%	0.08 ± 0.08	**3.4**
$\mu^-\phi$	3.2%	0.06 ± 0.06	**8.4**	$\mu^-\overline{K^{*0}}$	3.6%	0.45 ± 0.17	**7.0**
$e\text{-}\omega$	2.9%	0.30 ± 0.14	**4.8**	$\mu^-\omega$	2.4%	0.72 ± 0.18	**4.7**

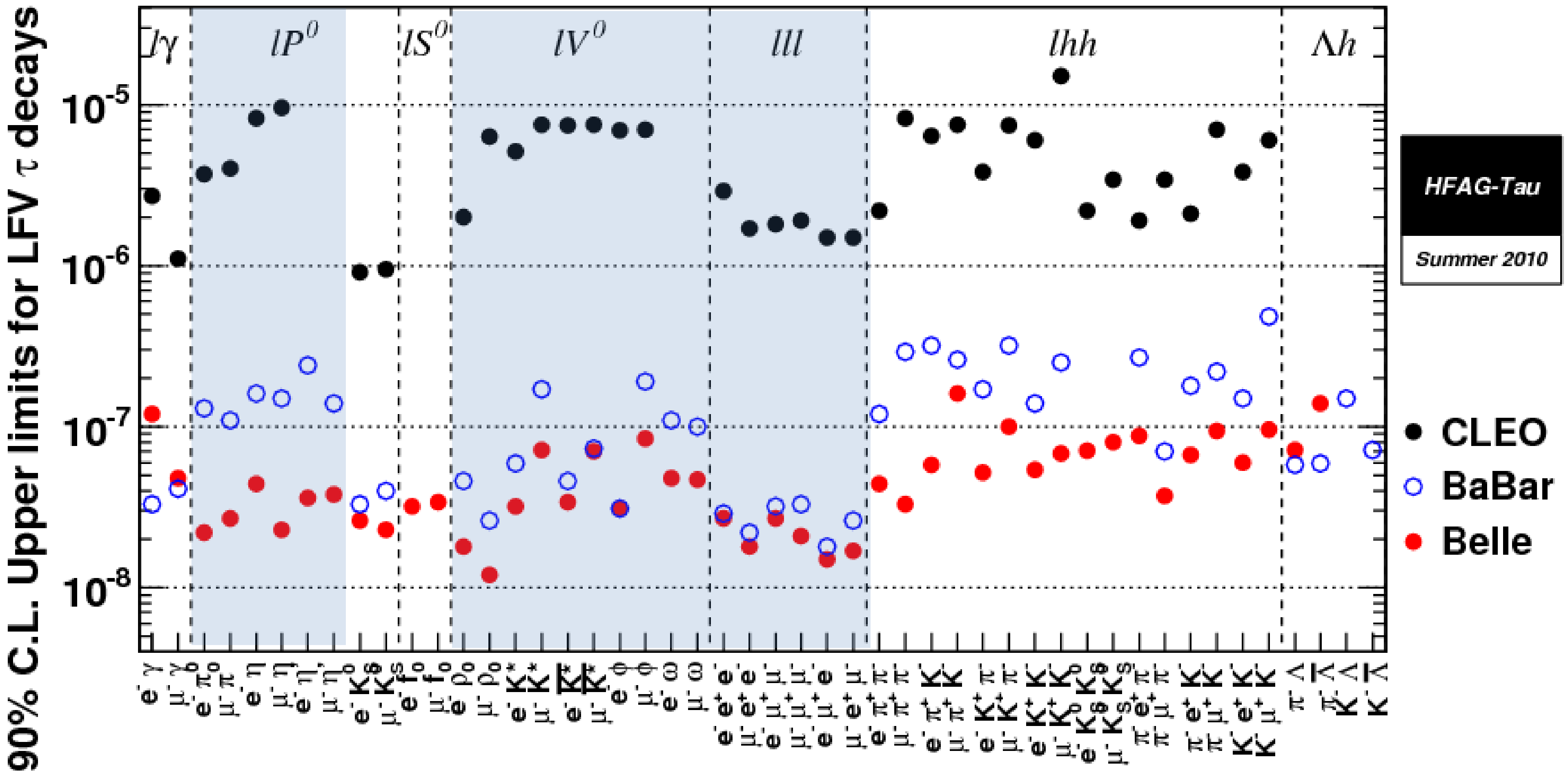
UL for $\tau \to \mu\rho^0$ is the most stringent among all the τ-LFV decays

Upper Limits on LFV τ Decay

At Spring on 2009



New Upper Limits on LFV τ Decay



Our sensitivity reaches $O(10^{-8})$!

100x more sensitive than CLEO's

LFV Sensitivity for future prospects

LFV sensitivity → depends on background level

50ab^{-1}@next-generation B-factories is expected.

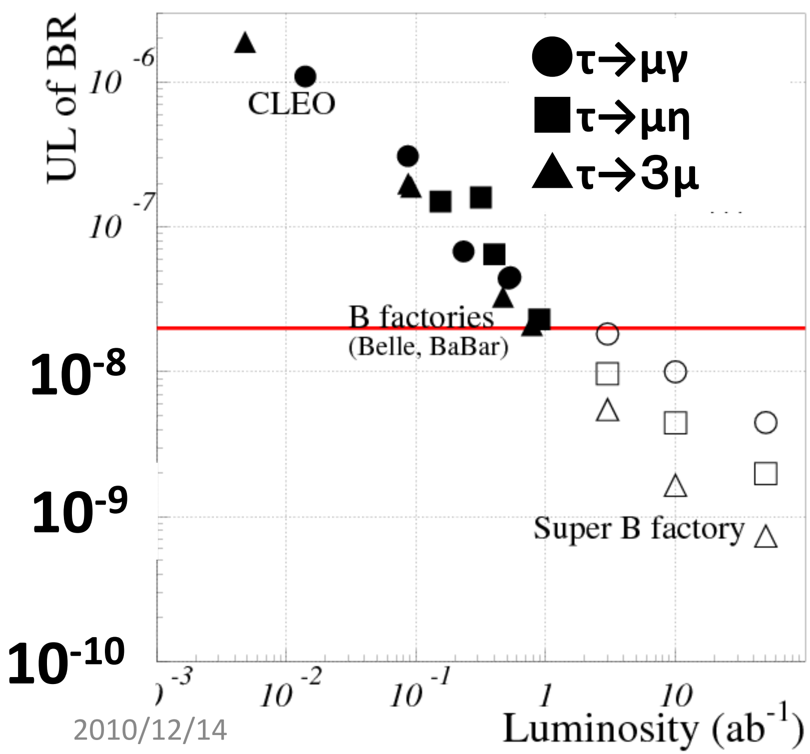
	N_{BG}@1ab^{-1}	N_{BG}@50ab^{-1}
$\tau \to \mu\gamma$	~7	~340
$\tau \to \mu\eta$	~0.7	~35
$\tau \to \mu\mu\mu$	~0.2	~8

simple extrapolation

$$\propto 1/\sqrt{Lum.}$$

⇕

$$\propto 1/Lum.$$



Expected sensitivity

$\tau \to \mu\gamma$ Br~O($10^{-(8-9)}$)

$\tau \to \mu\mu\mu$, $\mu\eta$ Br~O($10^{-(9-10)}$)

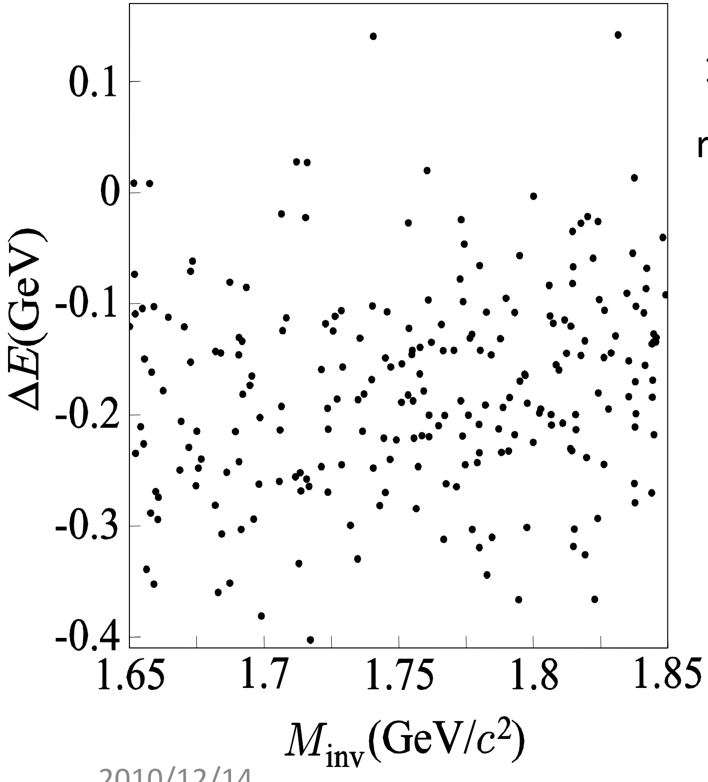
to obtain improved sensitivity

- better particle identification
- better resolution for γ

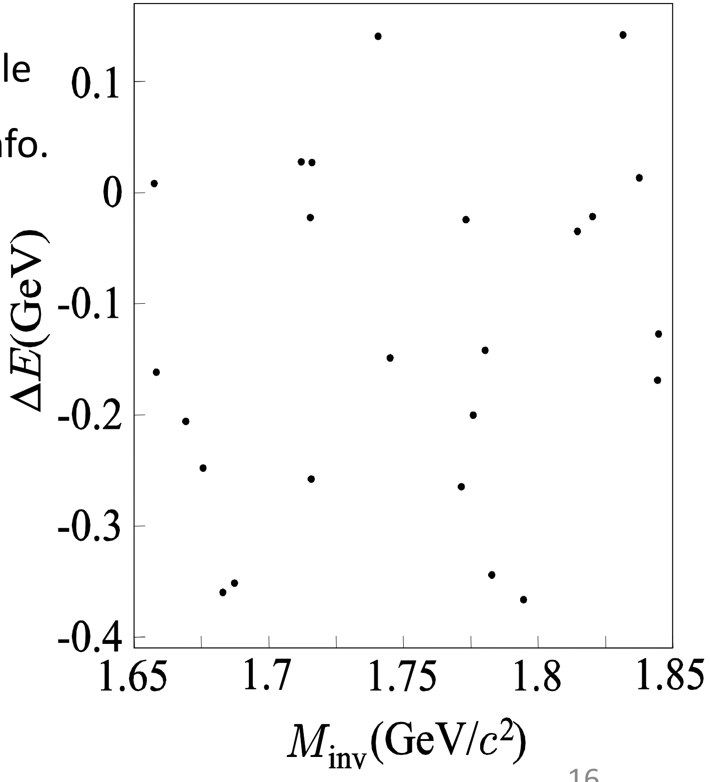
$\tau \rightarrow \mu\gamma$ & polarized beam

- According to our study, main BG comes from $\tau \rightarrow \mu\nu\nu$ + extra γ (ISR or beam BG).

➔This can not be rejected by PID.



1.5 ab^{-1} generic $\tau\tau$ MC sample removed by MC generator info.



nobody knows how $\tau \rightarrow \mu\gamma$ behaves

Theoretical calc. for $\tau \to \mu\gamma$

- Most generic form for int. Lagrangian

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\{m_\tau A_R \overline{\tau}\sigma^{\mu\nu} P_L \mu F_{\mu\nu} + m_\tau A_L \overline{\tau}\sigma^{\mu\nu} P_R \mu F_{\mu\nu} + \text{H.c.}\},$$

Consequently,

$A_L \neq 0, A_R = 0$ — μ in $\mu\gamma$ behaves similarly to π in $\pi\nu$

$A_L = 0, A_R \neq 0$ — μin $\mu\gamma$ behaves oppositely to π in $\pi\nu$

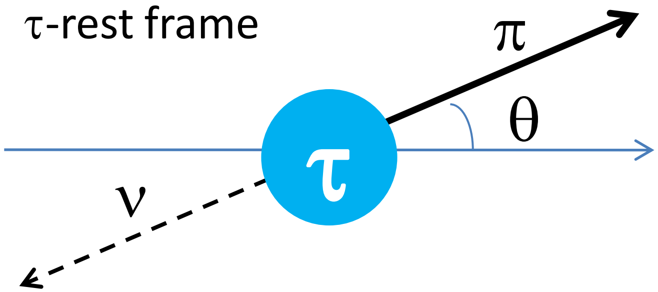
ex) SUSY SU(5) GUT

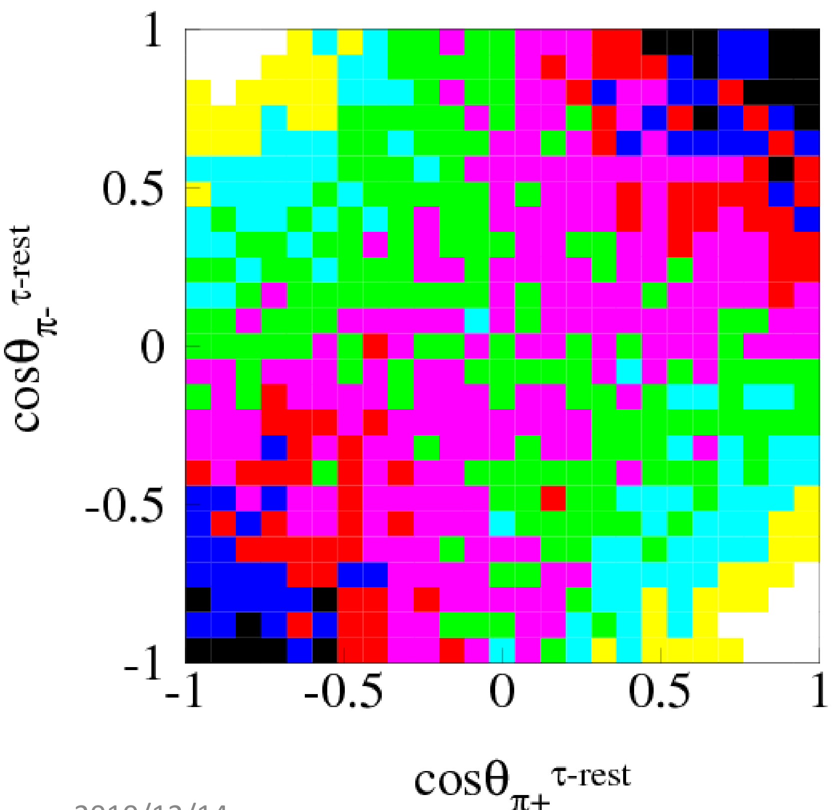
$A_L \neq 0, A_R = 0$

depends on $A_P \equiv \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}.$

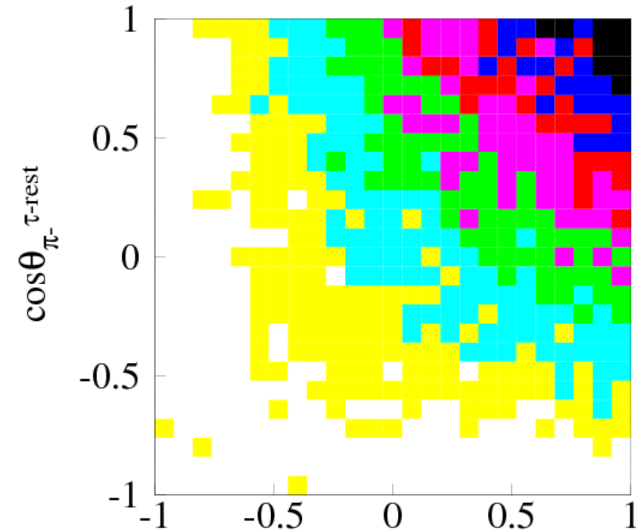
Phys.Rev. D63 (2001) 113003

$\tau^- \to \pi^- \nu / \tau^+ \to \pi^+ \nu$

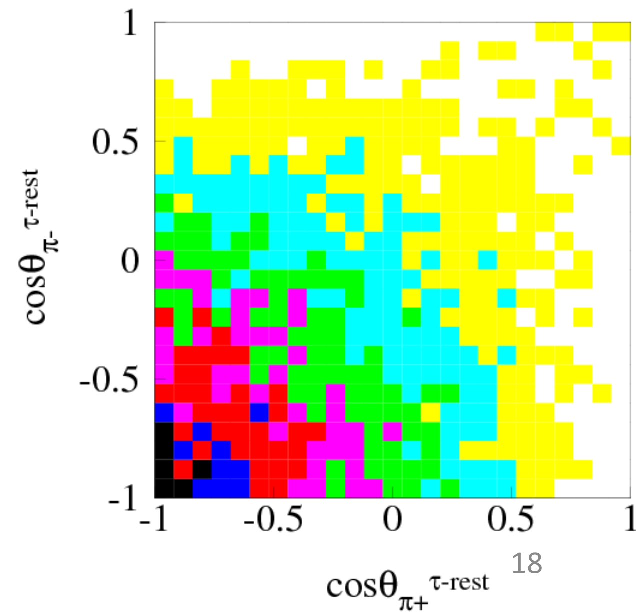




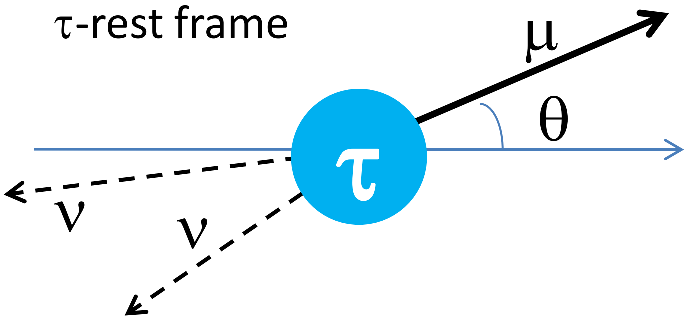
hel. of τ^- =1

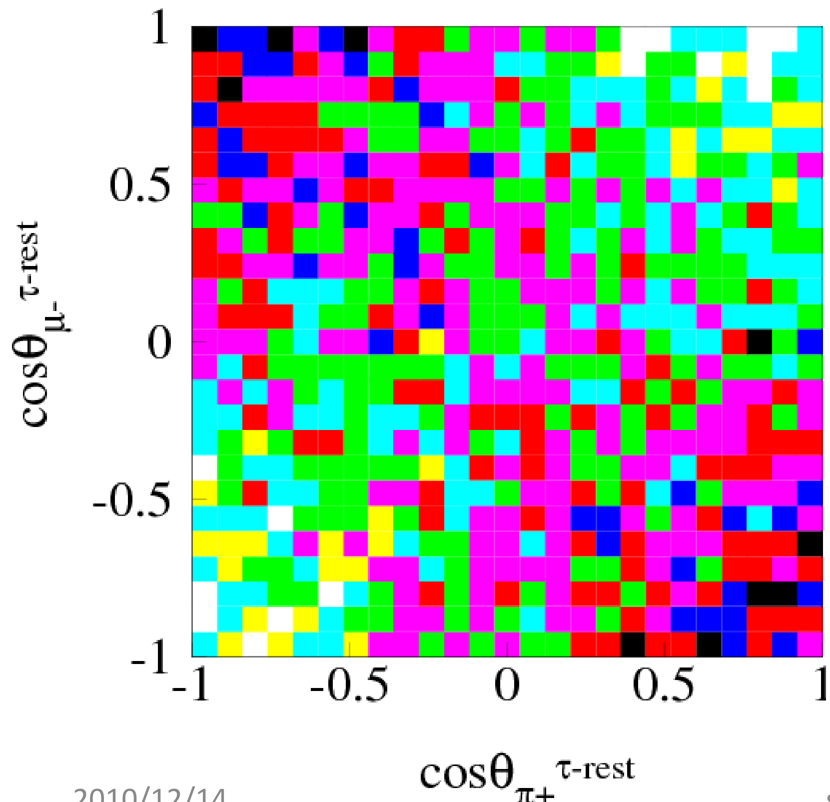


hel. of τ^- =-1

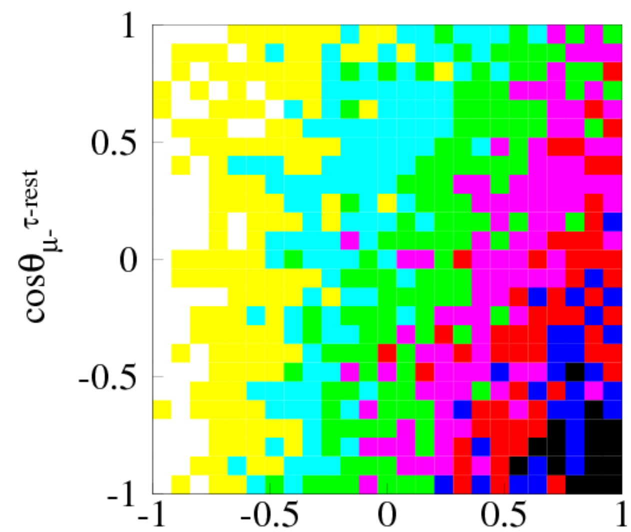


$\tau^- \to \mu^- \nu\nu / \tau^+ \to \pi^+ \nu$

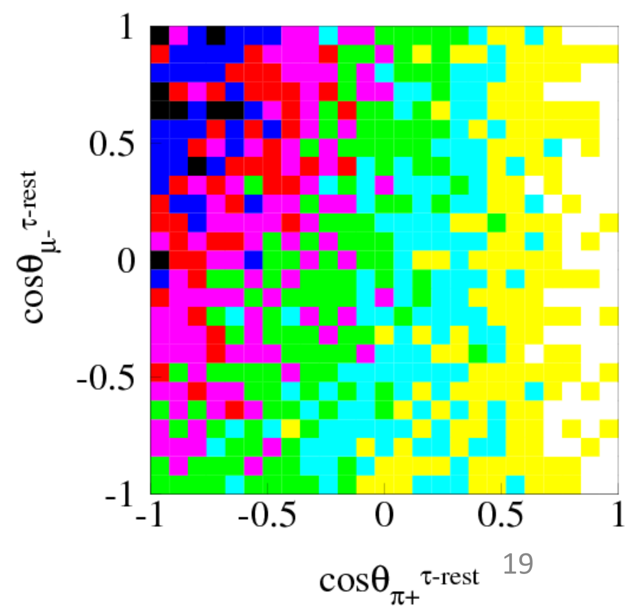




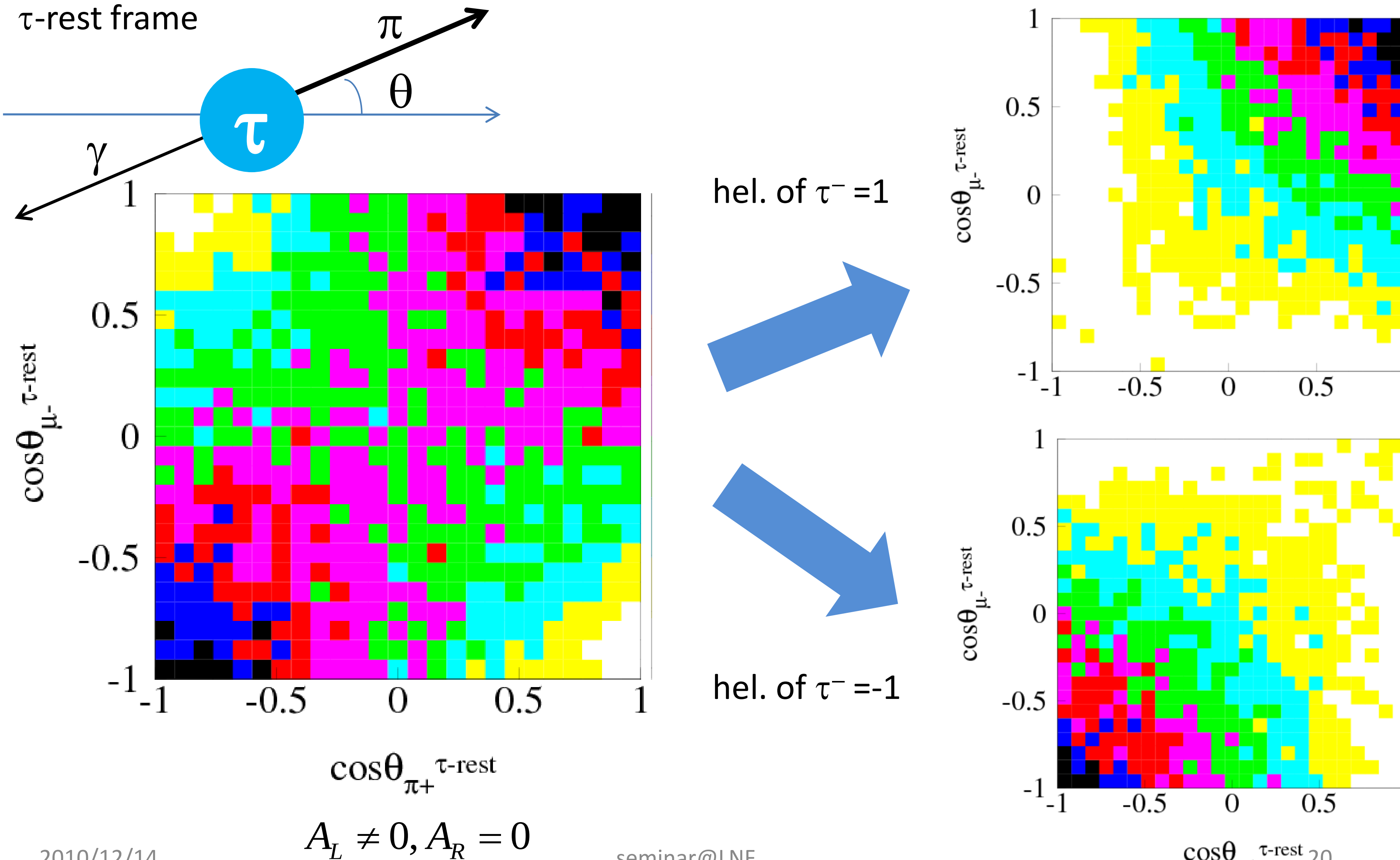
hel. of τ^- =1



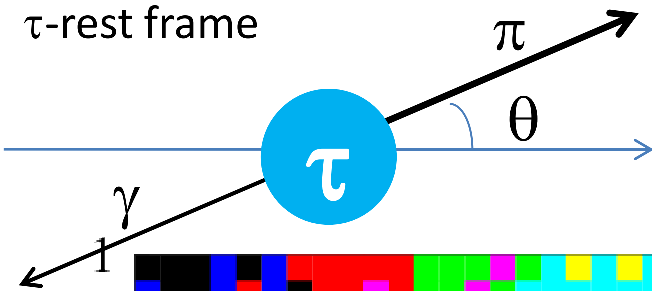
hel. of τ^- =-1

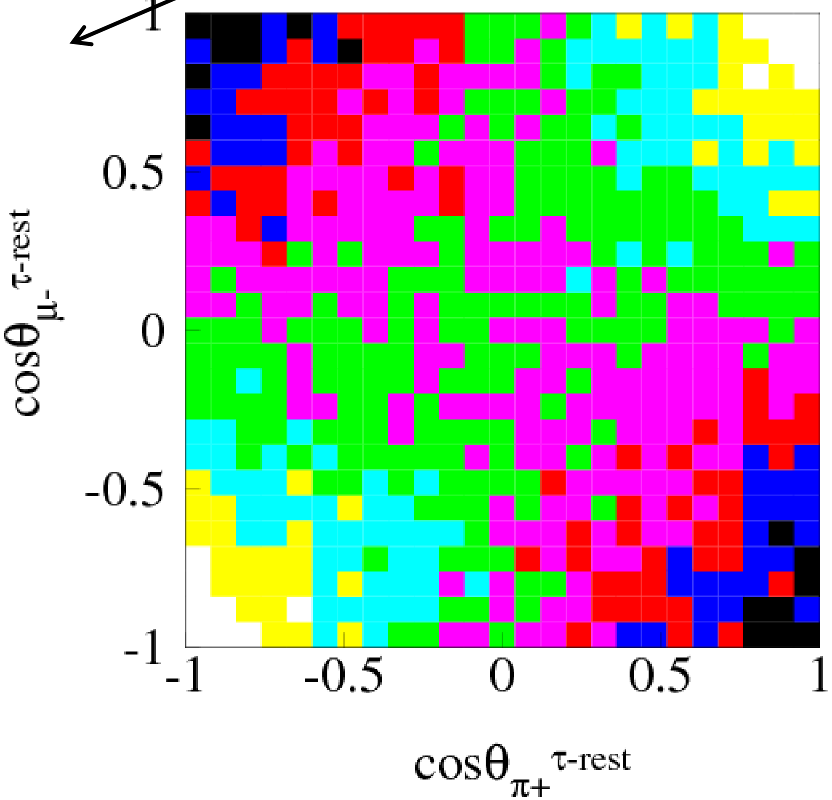


$\tau^- \to \mu^- \gamma(L) / \tau^+ \to \pi^+ \nu$



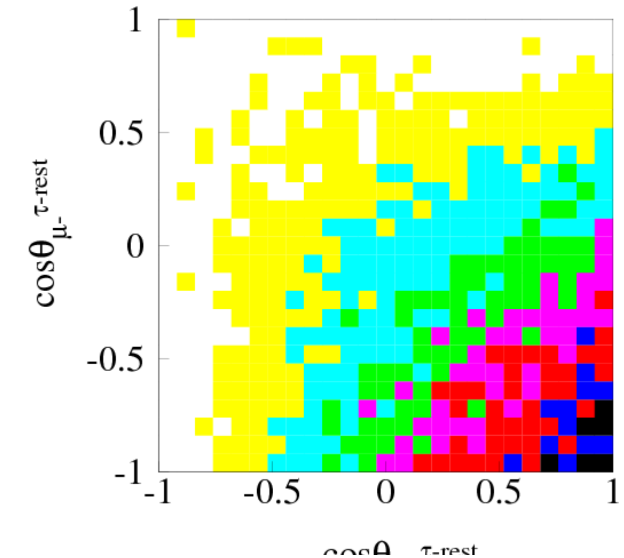
$\tau^- \to \mu^- \gamma(R) / \tau^+ \to \pi^+ \nu$



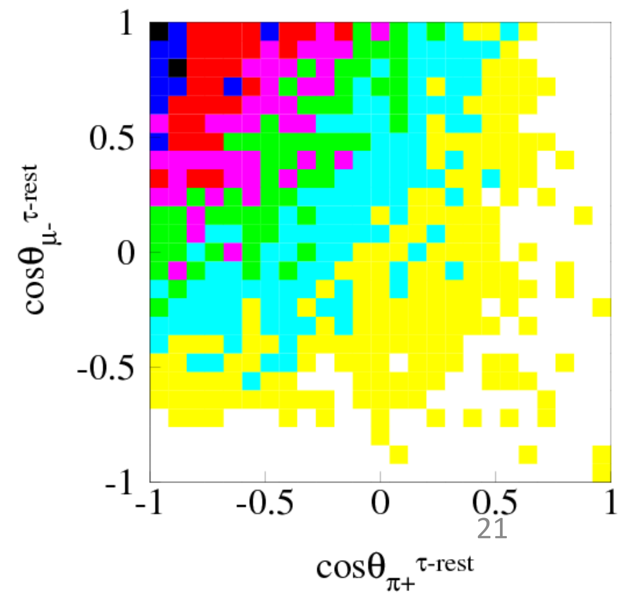


$A_L = 0, A_R \neq 0$

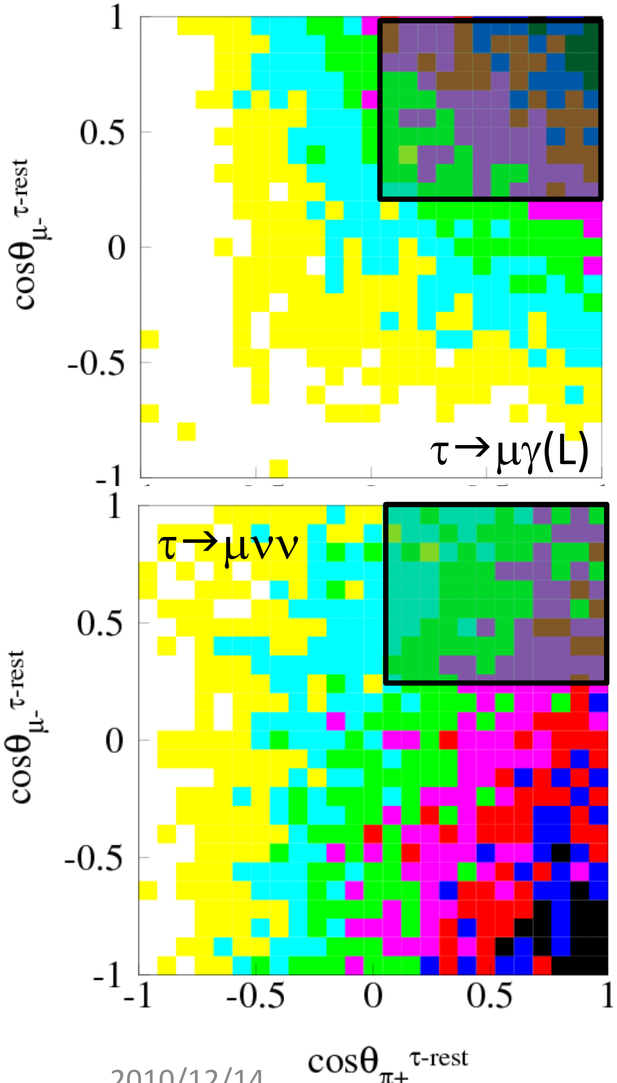
hel. of τ^- =1



hel. of τ^- =-1

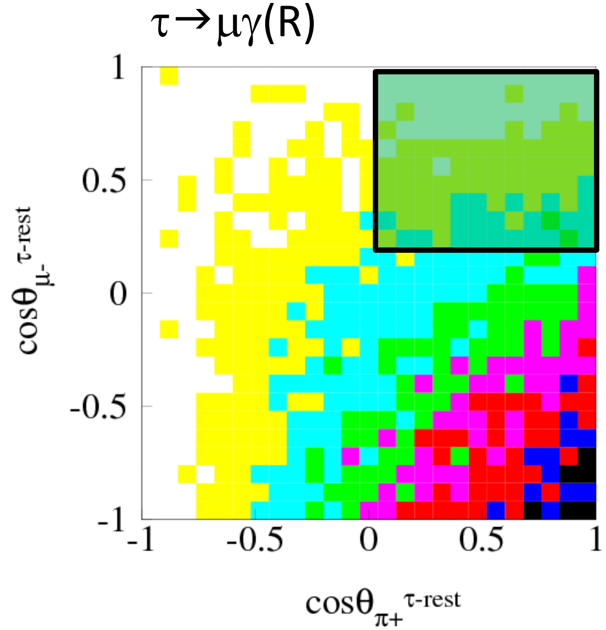


BG rejection?



The region $0.0<\cos\theta_{+}$, $0.2<\cos\theta_{-}$ is selected:

mode	Remain(%)
τ→μγ(L)	41%
τ→μγ(R)	13%
τ→μνν	23%

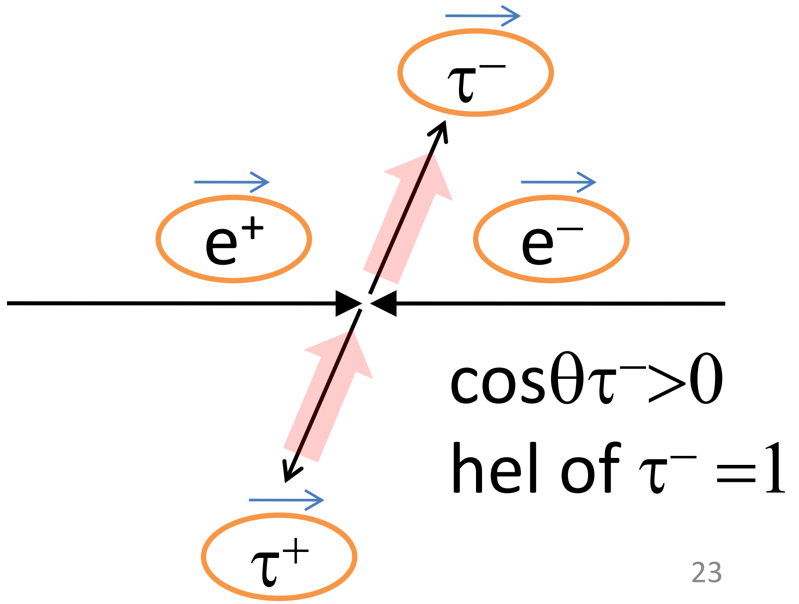


Simulation with Belle 1 detector

- set beam(3.5/8 GeV) and detector as current ones
  - 1-1 topology + 1 γ in signal side (E_γ>0.5GeV)
  - μID>0.95 P_μ>0.6GeV/c
  - 1.5<$M_{\mu\gamma}$<2.0, -0.5<ΔE<0.5 (GeV)
  - When μ and γ are decided, mother τ can be reconstructed. → τ-direction
  - helicity ~ polar angle for τ

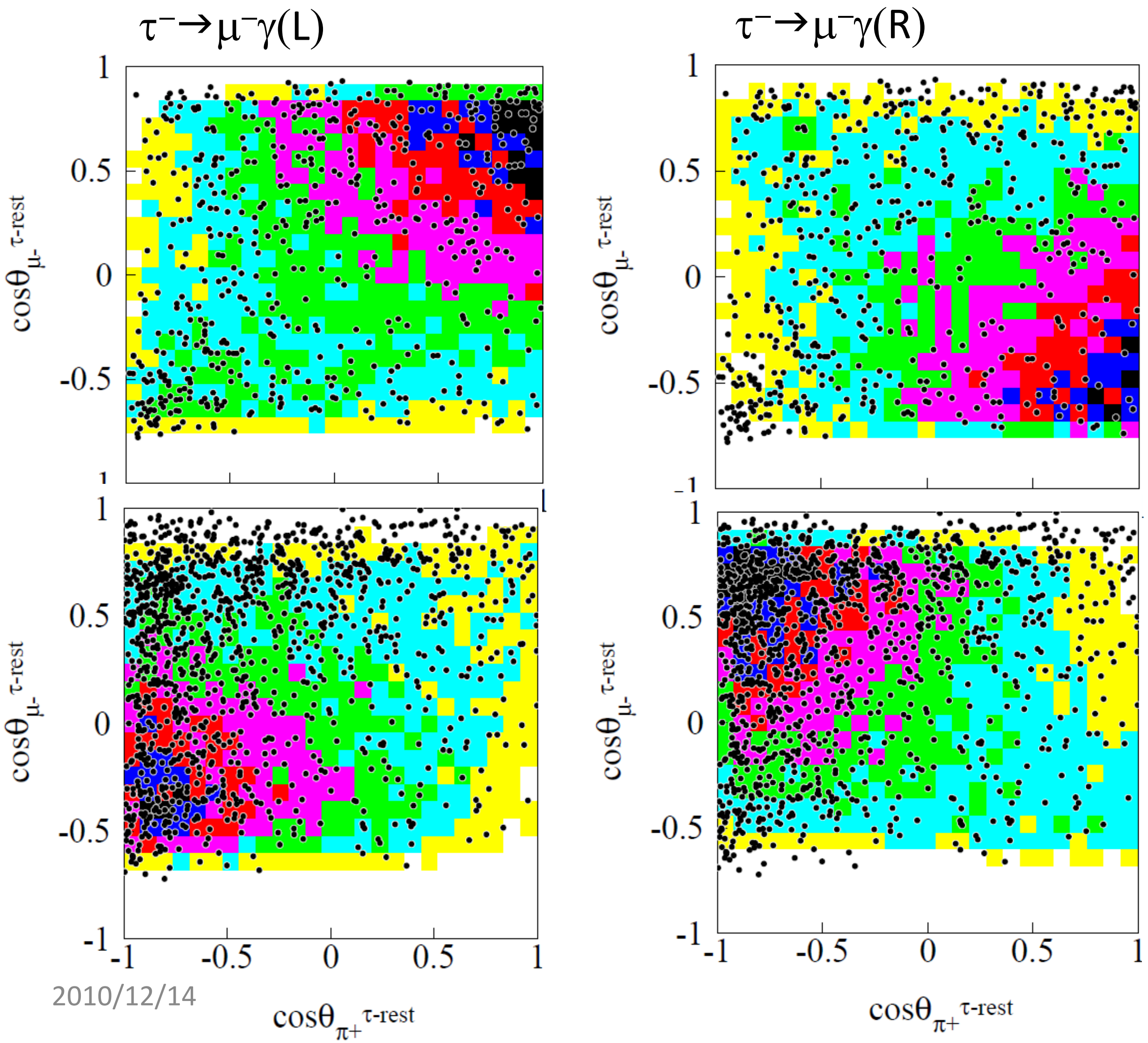
    ~ polar angle for μ

    in CM frame.



tau direction

from μ and γ, mother tau can be reconstructed and from it, another tau also can be reconstructed.(But, for BG, they are wrong information.)



dot:
$\tau^- \to \mu^- \nu\nu / \tau^+ \to \pi^+ \nu$

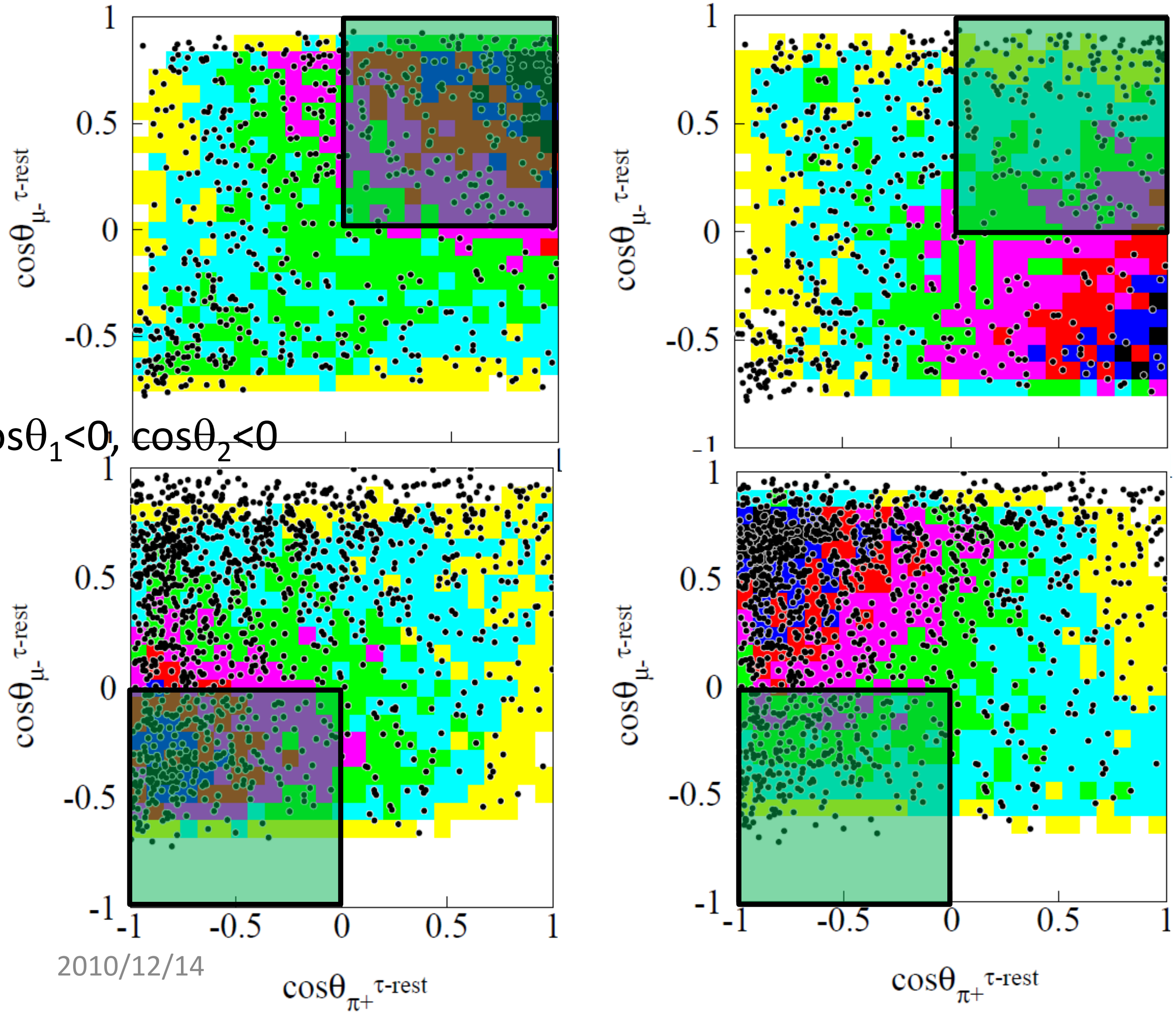
$\cos\theta\mu > 0$

$\cos\theta\mu < 0$

Selection

$\cos\theta_1>0$, $\cos\theta_2>0$

$\tau^-\to\mu^-\gamma(L)$ $\tau^-\to\mu^-\gamma(R)$



$\cos\theta_1<0$, $\cos\theta_2<0$

dot:
$\tau^-\to\mu^-\nu\nu/\tau^+\to\pi^+\nu$

$\cos\theta\mu>0$

mode	Remain(%)
$\tau\to\mu\gamma(L)$	38%
$\tau\to\mu\gamma(R)$	21%
$\tau\to\mu\nu\nu$	23%

$\cos\theta\mu<0$

Summary

Lepton flavor violation is a good signature of NP.

We have updated search for τ LFV decays into $\ell + M^0 (=\pi^0, \eta, \eta', \rho^0, \overline{K}^{*0}, K^{*0}, \omega, \phi)$ and $\ell\ell\ell$ using the world-largest data sample obtained by KEKB/Belle

No LFV signals are observed yet and we set limits of branching faction around $O(10^{-8})$.

→Improve sensitivity by factor ~100 from CLEO

- UL for $\tau \to \mu\rho^0$ is the most stringent among all the τ-LFV decays
- not only much larger data samples but also more effective BG rejection after detailed examination of the BG

In the future, SuperKEKB/SuperB projects will start with ~50x higher luminosity.

→BG will also increase propotionally to the luminosity.

→$\tau \to \mu\gamma$ will have huge BG events.

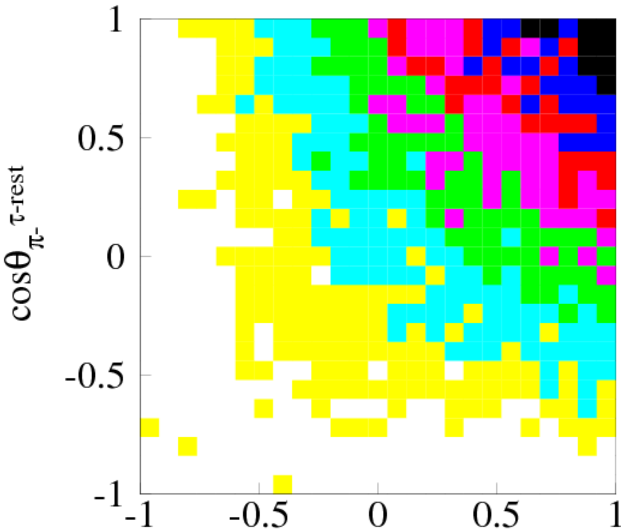
Beam polarization will help to reduce BG.

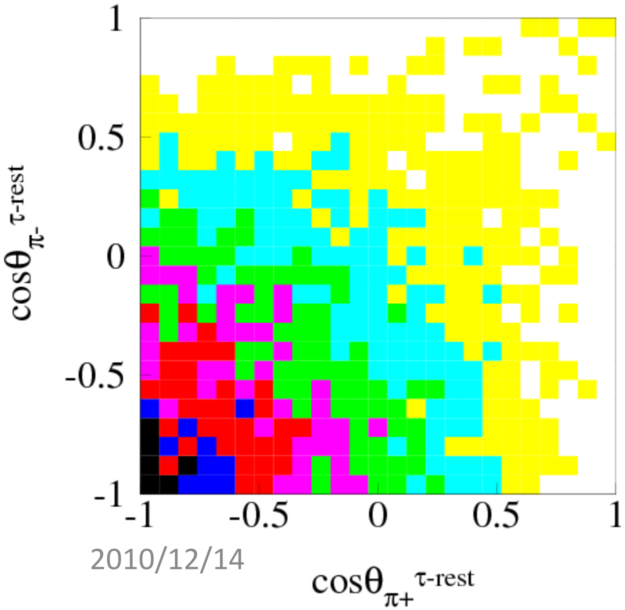
- L/R-type MC sample is considered. → hel. angle cut is sensitive to model.
- checked with actual-setteing data sample. → more realistic cut.

Belle started the analyses for the various modes using its full data sample!(~1ab^{-1})

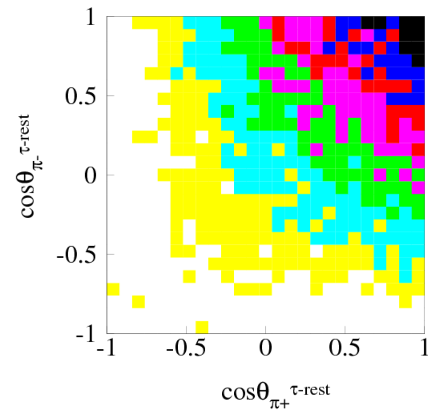
But., still, these figures for the angle of pi direction not to helicity but to tau direction.

To make them to the angle dist. to helicity.



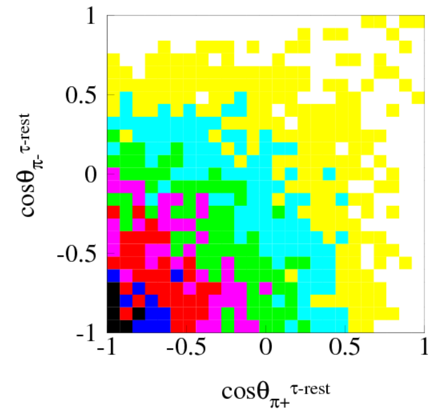


When the angle between helicity direction and pi direction, one signature of cosine should be oppsite. (Always, one tau direction corresponds to helicity direction while another direction is opposite to hel.)



exchange the sign

exchange the sign



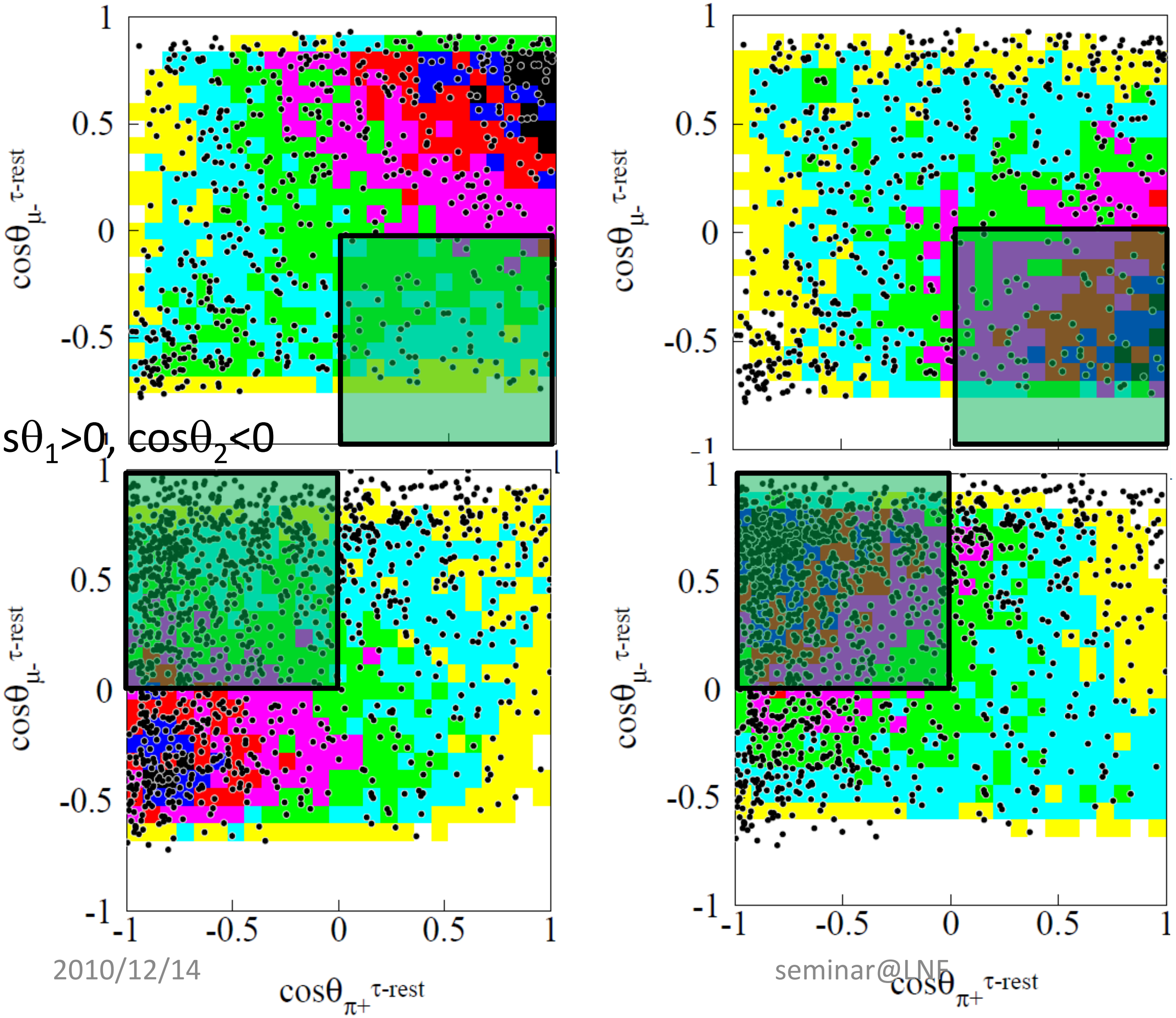
After that, unify them, you obtain the dist for the angle to helicity.

Selection

$\cos\theta_1<0$, $\cos\theta_2>0$

$\tau^- \to \mu^- \gamma$(L) $\tau^- \to \mu^- \gamma$(R)

$\cos\theta_1>0$, $\cos\theta_2<0$



dot:
$\tau^- \to \mu^- \nu\nu / \tau^+ \to \pi^+ \nu$

$\cos\theta\mu>0$

mode	Remain(%)
$\tau\to\mu\gamma$(L)	23%
$\tau\to\mu\gamma$(R)	41%
$\tau\to\mu\nu\nu$	40%

$\cos\theta\mu<0$

$\tau^- \to \mu^- \gamma$(general)/$\tau^+ \to \pi^+ \nu$

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\{m_\tau A_R \overline{\tau}\sigma^{\mu\nu}P_L \mu F_{\mu\nu} + m_\tau A_L \overline{\tau}\sigma^{\mu\nu}P_R \mu F_{\mu\nu} + \text{H.c.}\},$$

$$A_P \equiv \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}.$$

$$d\sigma(e^+e^- \to \tau^+\tau^- \to \mu^+\gamma + \pi^-\nu) = \sigma(e^+e^- \to \tau^+\tau^-)B(\tau^+ \to \mu^+\gamma)B(\tau^- \to \pi^-\nu) \times \frac{s}{s-4m_\tau^2}\,dz_\mu dz_\pi\left(1 - \frac{s(s-2m_\tau^2)}{(s-4m_\tau^2)(s+2m_\tau^2)} \times A_P(2z_\mu - 1)(2z_\pi - 1)\right), \quad (43)$$